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(54) Decision feedback equalizer for cancelling short- and long-multipath components using correspondingly delayed decision symbols

(57) In a decision feedback equalizer, transmitted signals are received by an array of antennas and baseband symbols are recovered. A forward filter provides weighting of the recovered baseband symbols with first coefficients so that precursor multipath components of a transmitted symbol are canceled and combines the weighted symbols. A set of first delay elements provide respective delays to one of the baseband symbols to produce a short- and a long-delayed baseband symbol. A set of correlators is provided for detecting correlations between the baseband symbol and the short- and long-delayed baseband symbols. A set of second delay elements provide respective delays to a decision symbol to produce a short- and a long-delayed decision symbol. A selector is responsive to a correlation detected by one of the correlators for selecting one of the short- and long-delayed decision symbols. A feedback filter shifts the selected decision symbol along a tapped-delay line to produce successively shifted decision symbols, multiplies them with second coefficients and combines the multiplied decision symbols to produce an output signal that cancels postcursor multipath components of the transmitted symbol. The output signals of the forward and feedback filters are combined to produce a pre-decision symbol which is used by a decision circuit to produce a decision output for coupling to the second delay elements as the aforesaid decision symbol.

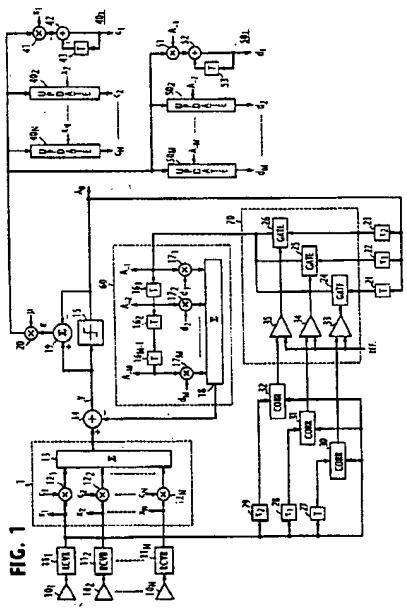

FIG. 1

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates generally to receivers which can be used for digital radio communication systems or sonar detection systems, and more specifically to a decision feedback equalizer with an array of antennas, or sensors for canceling multipath components of a signal received via time-varying multipath-fading channels.

Description of the Related Art

The combined use of an array of spaced antennas, or sensors with a decision feedback equalizer for canceling multipath-fading related intersymbol interference is known, as shown and described in EP-A 604, 956, published on January 6, 1994. Using the well known least mean square (LMS) algorithm, the main lobe of the antennas is oriented in the arrival direction of a target signal, while forming a null in the direction of an undesired signal. However, if multipath components are arriving through very long return paths, their delay times are likely to exceed the length of the tapped-delay line of the equalizer, and hence no equalization would result at all. In particular, as the data transmission speed of a channel grows faster, the delay profile of the transmitted signal normalized by modulation speed extends, increasing the severity of the problem.

SUMMARY OF THE INVENTION

A preferred embodiment of the present invention provides a decision feedback equalizer capable of canceling multipath-fading related intersymbol interference caused by very long multipath fading channels without increasing the length of the equalizer and canceling interference from jamming sources.

A further embodiment of the present invention provides a solution to a collision problem that occurs when multipath components (echoes) of an earlier transmitted symbol arrive at the equalizer simultaneously with those of a later transmitted symbol.

According to a first embodiment of the present invention, there is provided a decision feedback equalizer comprising sensor means for receiving transmitted signals and recovering baseband symbols from the received signals, forward filter means for weighting the recovered baseband symbols with first coefficients so that precursor multipath components of a transmitted symbol are canceled and combining the weighted baseband symbols to produce an output signal, a plurality of first delay means for providing delays to one of the baseband symbols of the sensor means to produce a short-delayed baseband symbol and a long-delayed baseband symbol, a plurality of correlator means for detecting correlations between the one of the baseband symbols and the short- and long-delayed baseband symbols, and a plurality of second delay means for providing delays to a decision symbol to produce a short-delayed decision symbol and a long-delayed decision symbol. Selector means is responsive to a correlation detected by one of the correlator means for selecting one of the short- and long-delayed decision symbols of the second delay means. Feedback filter means shifts the delayed decision symbol selected by the selector means along a tapped-delay line to produce successively shifted decision symbols, weighting the successively shifted decision symbols with second coefficients and combining the weighted decision symbols to produce an output signal that cancels postcursor multipath components of the transmitted symbol. The output signals of the forward and feedback filter means are combined to produce a pre-decision symbol. Decision means produces a decision output from the pre-decision symbol and applies the decision output to the plurality of second delay means as said decision symbol.

According to a second embodiment of the present invention, there is provided a decision feedback equalizer comprising sensor means for receiving transmitted signals and recovering therefrom baseband symbols, forward filter means for weighting the recovered baseband symbols with first coefficients so that precursor multipath components of a transmitted symbol are canceled and combining the weighted baseband symbols to produce an output signal, first delay means for providing a long delay to one of the baseband symbols from the sensor means to produce a long-delayed baseband symbol, first correlator means for detecting a correlation between the one of the baseband symbols and the long-delayed baseband symbol, second delay means for providing a long delay to a decision symbol to produce a long-delayed decision symbol, and third delay means for providing a first short delay to a decision symbol to produce a first short-delayed decision symbol. Selector means is responsive to the correlation detected by the first correlator means for selecting the long-delayed decision symbol of the second delay means. Feedback filter means multiplies the first short-delayed decision symbol from the third delay means by a second coefficient to produce a first output signal that cancels a postcursor multipath component of the transmitted symbol, and successively shifts the long-delayed decision symbol selected by the selector means along a tapped delay line to produce successively shifted

decision symbols, multiplies the successively shifted decision symbols by third coefficients, and combines the multiplied decision symbols to produce a second output signal that cancels postcursor multipath components of an earlier-transmitted symbol. The output signals of the forward and feedback filter means are combined to produce a pre-decision symbol, which is fed to decision means to produce a decision output which is applied to the second and third delay means as said decision symbol.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be described in further detail with reference to the accompanying drawings, in which:

Fig. 1 is a block diagram of a decision feedback equalizer using an adaptive filter array according to an embodiment of the present invention;

Fig. 2 is a diagram illustrating a simplified antenna array;

Figs. 3A and 3B show antenna patterns obtained respectively by computer simulations of the equalizer of the present invention and a prior art equalizer having no feedback filter;

Fig. 4 is a block diagram of a modified decision feedback equalizer of the present invention; and

Fig. 5 is a block diagram of a further modification of the present invention.

DETAILED DESCRIPTION

Referring now to Fig. 1, there is shown a DFE (decision feedback equalizer) receiver according to a first embodiment of the present invention. The receiver is most suitably used for applications such as digital radio communication systems or sonar detection systems where the quality of a transmitted signal is seriously affected by multipath components of the signal. At the transmit site, a symbol sequence {.....a_{-1}, a_0, a_{+1}.....} is quadrature-modulated onto a carrier in a format such as phase shift keying and transmitted. The receiver comprises an array of antennas 10_1 - 10_N spaced at half-wavelength intervals of the transmitted carrier, a plurality of receivers 11_1 - 11_N, and an adaptive array filter 1 formed by a plurality of complex multipliers 12_1. 12_N and an adder 13. The outputs of antennas 10_1 - 10_N are connected respectively to receivers 11_1 - 11_N where they are quadrature-demodulated, recovering baseband vectors x_1, x_2, ... x_N. These baseband vectors are applied to complex multipliers 12_1 - 12_N, where they are respectively multiplied by weight coefficients c_1, c_2, ..., c_N supplied from coefficient update circuits 40_1 - 40_N, so that precursors (future symbols) of multipath-fading related intersymbol interference are canceled. The weighted vectors are summed together in combiner 13.

The output of the adaptive array filter 1 is applied to a subtractor 14 where it is combined with a postcursor canceling signal supplied from a feedback filter 60 to produce an equalized output vector "y" at the output of subtractor 14. The output of subtractor 14 is coupled to a decision circuit 15 for making a decision in favor of logic-1 or logic-0 depending on the result of a comparison with a threshold value, producing a sequence of estimated symbols $\{a_i\}$.

An error detector 19 is connected across the input and output of decision circuit 15 to detect a decision error e which is suitably weighted by a correction factor μ in a multiplier 20 and supplied to update circuits 40_1 - 40_N. Each update circuit 40 includes a complex correlator 41 in which the weighted decision error $\mu \cdot \varepsilon$ is multiplied by the corresponding incoming symbol x_i^* (where (*) represents the complex conjugate, and i = 1, 2, ..., N). The weight coefficient c_i is produced by coupling the output of correlator 31 to the negative input of a subtractor 42 and applying its output through a symbol delay (T) element 43 to the other input of subtractor 42 forming a feedback loop so that it operates according to the LMS (least mean square) algorithm $c_i^n = c_i^{n-1} - \mu\, x_i^* \varepsilon$ (where n is the time indicator) and hence the mean square value of the decision error ε is reduced to a minimum. Note that the decision circuit 15, decision error detector 19, feedback filter 60 and tap-weight update circuits 50_1 - 50_N form a decision feedback equalizer.

Postcursors (previous symbols) of multipath-fading related intersymbol interference are canceled by coupling the output of decision circuit 15 to the feedback alter 60 through a selector circuit 70.

The feedback filter 60 comprises an M-stage tapped-delay line having symbol-delay elements 16_1 - 16_M. When a transmitted symbol A_0 is reproduced at the output of decision circuit 15, M past decision output symbols A_{-1}, A_{-2}, ..., A_{-M} appear at the successive taps of the M-stage delay line and are presented to complex multipliers 17_1, 17_2, ..., 17_M, respectively, where they are weighted by tap-weight coefficients d_1, d_2, ..., d_M, respectively. The weighted tap signals are summed in an adder 18 to produce a postcursor canceling signal which is applied to the subtractor 14 where it is subtracted from the output of adder 13.

The tap-weight coefficient d_j (where j = 1, 2, ..., M) is produced according to the LMS algorithm $d_j^n = d_j^{n-1} + \mu\, A_{-j}^* \varepsilon$. Specifically, the output of the decision error detector 19 is coupled to tap-weight update circuits 50_1 - 50_M. Each update circuit 50 includes a correlator 51 for multiplying the weighted decision error $\mu \cdot \varepsilon$ by complex conjugate of past decision output symbol A_{-j}, the output of correlator 51 being coupled to one input of an adder 52 whose output is connected through a symbol delay (T) element 53 to the other input of adder 52.

The DFE includes a plurality of delay elements 21, 22 and 23. One of the outputs of delay elements 21, 22, 23 is selected by selector circuit 70. Delay elements 21, 22 and 23 are connected to the output of decision circuit 15 to provide a delay time corresponding to T, τ_1 and τ_2, respectively, to decision symbol A_0. Note that the delay time τ_1 is greater than M x T, i.e., greater than the total delay time of feedback filter 60. The delay time τ_2 is also greater than τ_1. Delay times T, τ_1 and τ_2 are the delay times of multipath components of a transmitted symbol a_0 and the T-delayed multipath component is a near-field reflection and the τ_1- and τ_2-delay times are far-field reflections propagating over long paths. The occurrences of these far-field components are known in advance from experiments. Typically, τ_1 and τ_2 are 100T and 200T, respectively.

A plurality of delay elements 27, 28 and 29 are connected to the output of receiver 11_1 to provide delays T, τ_1 and τ_2, respectively, to the received baseband symbol x_1.

Correlations between the symbol x_1 and the outputs of delay elements 27, 28 and 29 are detected by correlators 30, 31 and 32, respectively. If multipath components of delays T, τ_1 and τ_2 exists for a given transmitted symbol and arrive in sequence, correlators 30, 31 and 32 will sequentially produce their output signals.

Selector 70 includes comparators 33, 34 and 35 and gates 24, 25 and 26. Comparators 33, 34 and 35 are connected to the outputs of correlators 30, 31, 32, respectively, for making comparisons with a predetermined reference value, and supply their outputs to gates 24, 25, 26, respectively. If the output of a corresponding correlator exceeds the reference value, each comparator supplies a gate-on pulse to the associated gate for coupling a delayed decision symbol to the feedback filter 60.

Assume that a transmitted symbol a_0 has a multipath component arriving at an instant delayed by symbol interval T with respect to the symbol a_0, a correlation is detected between them by correlator 30 and a gate-on pulse is supplied from comparator 33 to gate 24 to pass the output of delay element 21 to the feedback filter 60. Therefore, a decision output symbol A_0 corresponding to the transmitted symbol a_0 appears at the output of delay element 21 as a past symbol A_{-1} time-coincident with the detection of the corresponding T-delayed multipath component by correlator 30. This past symbol is applied through gate 24 to the first tap of feedback filter 60, where it is weighted by coefficient d_1 for coupling to adder 18, a postcursor canceling output A_{-1} d_1 at the output of adder 18. Using this canceling signal, the T-delayed multipath component is canceled at the output of subtractor 14.

The decision symbol A_{-1} will then be shifted from delay element 16_1 to the next element 16_2 and appears at the second tap as a past decision symbol A_{-2} and weighted by coefficient d_2. If there is a 2T-delayed multipath component associated with the transmitted symbol ao, the update circuit 50-2 will update the coefficient d_2 using the weighted decision error $\mu \cdot \varepsilon$ and so the past symbol A_{-2} is weighted with the updated coefficient d_2, producing a canceling signal. This canceling signal is time coincident with the 2T-delayed multipath component which appears at the output of combiner 13 at the instant two symbols delayed with respect to the symbol a_0. A 3T-delayed multipath component, if present, will be canceled in a similar manner by a canceling signal A_{-3} d_3.

Therefore, multipath components of a given transmitted symbol are canceled in this manner insofar as their longest delay does not exceed the total delay time of feedback filter 60.

Quantitative analysis of the cancellation of multipath components whose longest delay does not exceed the total delay time of feedback filter 60 will be given below using simultaneous linear equations. It will also be shown that the adaptive array filter 1 operates in the same manner as a feedforward filter which usually forms part of a decision feedback equalizer.

First, the output "y" of subtractor 14 is given in the form:

$$y = [c_1, c_2, \ldots\ldots c_N] \begin{bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_N \end{bmatrix} + [d_1, d_2, \ldots\ldots d_M] \begin{bmatrix} A_{-1} \\ A_{-2} \\ \cdot \\ \cdot \\ A_{-M} \end{bmatrix} \qquad (1)$$

Since the past decision symbol can be approximated as a transmitted symbol if the symbol error rate can be ignored, the decision error ε is given by:

$$\varepsilon = y - a_0 \qquad (2)$$

The weight coefficients c_i and d_j that minimize the mean square value of decision output e are determined by a normal equation (Wiener-Hoph Equation) using the orthogonality principle. From the following relations, the normal Equation can be derived, using linear weight coefficients as unknown variables.

$$E[\varepsilon \cdot x_i^*] = 0 \ (i = 1, 2, \ldots, N) \qquad (3)$$

$$E[\varepsilon \cdot a_j^*] = 0 \ (j = -1, -2, \ldots, -M) \quad (4)$$

where E represents the expectation.

A simplified antenna array of the embodiment of Fig. 1 is illustrated in Fig. 2 to derive the normal equation using a simplified dispersive propagation model. Let hi represent the impulse response of a propagation path, with h_0 representing a reference impulse response for the symbol of interest. The impulse responses h_{-i} and h_{+i} represent the precursor and the postcursor, respectively. The received signals are represented by convolution of the transmitted symbol sequence $\{a_i\}$ and the impulse response h_i. The main signal component S_i received by each antenna is given by $h_0 a_0$ and a multipath component received by each antenna is given by hi a_{0-i}.

Because of the 1/2 antenna spacing, the main signal component S_i received by antenna 10_i is delayed by an amount equal to exp $\{-j(i-1)\phi_0\}$ with respect to the main component S 1 received by the first antenna 101, where ϕ_0 is the angle of arrival of the main signal Si to the axis of each antenna and is given by $\phi_0 = \pi \sin \theta_0$. Therefore, the baseband vectors xi are represented as follows:

$$x_i = \sum_{n=-\infty}^{+\infty} h_n \exp\{-j(i-1)\phi_n\} a_{0-n} + n_i \quad (5)$$

where n_i is the noise contained in the output of antenna 10_i and ϕ_n represents the angle of arrival of a multipath signal component corresponding to the n-th impulse response of the dispersive propagation model and is given by $\phi_n = \pi \sin \phi_n$. From Equations (3) and (4), the normal Equation is given as follow:

$$\begin{bmatrix} \Psi_{pq} & -H^* \\ H^T & -I \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix} = \begin{bmatrix} S \\ 0 \end{bmatrix} \quad (6)$$

9 where, C and D are in the form

$$C = \begin{bmatrix} c_1 \\ c_2 \\ . \\ . \\ c_N \end{bmatrix}, \ D = \begin{bmatrix} d_1 \\ d_2 \\ . \\ . \\ d_M \end{bmatrix} \quad (7)$$

ψ_{pq} represents the N x N correlation matrix of signals received by antennas 10_1 - 10_N and the elements of this matrix are given by:

$$\Psi_{pq} = \left[\sum_{n=-\infty}^{+\infty} h_n^* \cdot h_n \cdot \exp\{j(p-q)\phi_n\} \cdot \sigma^2 \cdot \delta_{pq} \right] \quad (8)$$

where p, q = 1, 2, ..., N, σ^2 is the noise power, δ_{pq} is the Kronecker's delta which equals 1 if $\pi = \theta$ or 0 if $\pi \neq \theta$, I is an M x M unit matrix, and 0 is an M-th order zero vector, H is the N x M correlation matrix of the feedback filter 60 given by Equation (9), and S is a correlation vector correlating the symbol vector (x_1, x_2, ... x_n) with the decision output symbol as given by Equation (10).

$$H = \begin{bmatrix} h_1 & \cdots & h_M \\ h_1 \cdot \exp\{-j\phi_1\} & \cdots & h_M \cdot \exp\{-j\phi_M\} \\ h_1 \cdot \exp\{-j2\phi\} & \cdots & h_M \cdot \exp\{-j2\phi_M\} \\ . & \cdots & . \\ . & \cdots & . \\ . & \cdots & . \\ h_1 \cdot \exp\{-j(N-1)\phi_1\} & \cdots & h_M \cdot \exp\{-j(N-1)\phi_M\} \end{bmatrix} \quad (9)$$

$$S = h_0 * \begin{bmatrix} 1 \\ \exp\{j\phi_0\} \\ \exp\{j2\phi_0\} \\ \cdot \\ \cdot \\ \cdot \\ \exp\{j(N-1)\phi_0\} \end{bmatrix} \quad (10)$$

Equation (6) indicates that the operation of the antenna array and the feedback filter is represented by simultaneous linear equations and that the antenna array functions as a feedforward filter of the decision feedback equalizer. Therefore, the present embodiment is not simply a sum of, but an integrated combination of, an antenna array and a decision feedback equalizer.

A computer simulation was made for evaluating the present embodiment in terms of the directivity pattern of the antenna array which is given by:

$$P(\theta) = |C^T \cdot \Gamma| = |\sum_{n=1}^{n=N} c_n \cdot \exp\{-j(n-1)\phi(\theta)|| \quad (11)$$

where, Γ is a unit DC signal vector that is assumed to be arriving at antennas 10_1 - 10_N at an angle q and is given by:

$$\Gamma^T = 1 \cdot [1 \exp\{-j\phi(\theta)\}\exp\{-j2\phi(\theta)\} .....\exp\{-j(N-1)\phi(\theta)\}| \quad (12)$$

where $\phi(\theta) = \pi \sin \theta$.

In the computer simulation, a four-element antenna array (each element with a 10 dB signal-to-noise ratio) and a single-delay tap feedback filter were used for a three-wave multipath fading model by representing a main signal as $h_0 a_0$, a phase-advanced multipath component as $h_{-1} a_{+1}$, and a phase-lagged multipath component as $h_{+1} a_{-1}$, and setting the amplitude of the impulse responses to a unit value (i.e., $|h_{-1}| = |h_0| = |h_{+1}| = 1$, which represents the worst situation where the frequency selective fade is dominant) and setting the arrival angle of the main signal (θ_0), phase-advanced and lagged multipath components (θ_{-1}) and (θ_{+1}) as $\theta_0 = 20°$, $\theta_{-1} = 45°$ and $\theta_{+1} = 20°$, respectively. For purposes of comparison, a simulation was further made on a prior art four-element adaptive array receiver having no feedback filter, using the same operating parameters just described. Results of the computer simulations are shown in Figs. 3A and 3B.

The antenna pattern shown at Fig. 3A is the result of the simulation derived from a four-element antenna array embodying the present invention. It is seen that the main lobe is oriented in the arrival direction (θ=20°) of the main signal and a null point (a point of zero gain) is formed in the arrival direction of the phase-advanced multipath component. While the phase-lagged multipath component $h_{+1} a_{-1}$ is summed with the main signal, it is cancelled with an estimate of the symbol a_{-1} derived from the first delay-line tap of the feedback filter. It is therefore seen that, regardless of the presence of multipath components of a desired signal, the directivity pattern of the antenna array is constantly oriented in the arrival direction of the main component of the desired signal so that it is received at a maximum signal-to-noise ratio. On the other hand, the directivity pattern shown at Fig. 3B is the result of simulation derived from the prior art adaptive array receiver. Since the prior art receiver has no feedback filter and provides cancellation by forming null points in the antenna pattern, it is impossible to cancel the phase-lagged multipath component $h_{+1} a_{-1}$ from the main component with which it is received with the same antenna gain. As a result, the reduction of the phase-lagged multipath component would cause the antenna gain to be reduced at the cost of the main signal.

If the delay times of multipath components exceed the total delay time of the feedback filter, no equalization proceeds in the feedback filter until correlation is detected again. Under such conditions, the normal equation is given in the form:

$$\begin{bmatrix} \Psi_{pq} & 0 \\ 0 & -I \end{bmatrix} \begin{bmatrix} C \\ D \end{bmatrix} = \begin{bmatrix} S \\ 0 \end{bmatrix} \quad (13)$$

Such conditions correspond to a receiver having no feedback filter, where an antenna pattern similar to that of Fig. 3B would result.

Multipath components whose delay times exceed the total delay time of the feedback filter 60 may be few or nonexistent under normal multipath fading environment. However, very long delay paths may exist in a particular situation such as sonar and the like and multipath components coming through such long paths experience delays equal to or greater than (τ_1. Therefore, if there is a τ_1-delayed multipath component for a given transmitted symbol a_0, a correlation is detected between a_0 and the τ_1 component by correlator 31 and a gate-on pulse is supplied from comparator 34 to gate 35 to pass the output of T-delay element 22 to the feedback fiter 60. Therefore, a decision output symbol A_0 corresponding to the transmitted symbol a_0 appears at the output of delay element 22 simultaneously with the time of detection of the corresponding τ_1-delayed multipath component. This past symbol is applied through gate 25 to the first tap of feedback filter 60 as a past symbol $A_{-\tau 1}$, where it is weighted by coefficient d_1, producing a postcursor canceling signal $A_{-\tau 1} \cdot d_1$ at the output of adder 18. Using this signal, subtractor 14 cancels the (τ_1-delayed multipath component. If the τ_1-delayed multipath component is followed by a series of multipath components at successive T (symbol) intervals, such multipath components will be adaptively canceled as the decision symbol $A_{-\tau 1}$ is successively shifted along the tapped-delay line of the feedback filter. This process continues until the decision symbol $A_{-\tau 1}$ appears as $A_{-(\tau 1-M)}$ at the end of the tapped-delay line of the feedback filter. This process can be represented by the following normal equation;

$$\begin{bmatrix} \Psi_{pq} & 0 & -H^* \\ 0 & 0 & 0 \\ H^T & 0 & -I \end{bmatrix} \begin{bmatrix} C \\ D \\ D' \end{bmatrix} = \begin{bmatrix} S \\ 0 \\ 0 \end{bmatrix} \qquad (14)$$

where, D' indicates the vector of tap-weight coefficients d_i of the feedback filter when the τ_1-delayed symbol is being shifted along its tapped-delay line, and D indicates the vector of tap-weight coefficients d_i of the feedback filter when the T-delayed symbol is being shifted along its tapped-delay line. The vector D no longer exists when D' exists and hence D = 0 in Equation (14). It is seen from Equation (14) that the size of the correlation matrix of Equation (13) is extended from (N + M) x (N + M) to (N + M + τ_1) x (N + M + τ_1).

Similar events occur when multipath components of a transmitted symbol return at instants delayed by amount equal to τ_2 or greater.

The multipath components of an earlier-transmitted symbol may arrive at the same instants as a significant multipath component of the most recent symbol. Under such circumstances, correlations will be simultaneously detected by correlators 30 and 31 to open the gates 24 and 25. When this occurs, equalization cannot proceeds in the feedback filter of Fig. 1.

A solution to this problem is illustrated in Fig. 4 as a modification of the first embodiment of this invention. According to this embodiment, the modified DFE receiver includes feedback filter 60' and includes only delay elements 22, 23, 28, 29 and correlators 31, 32. Modified selector circuit 70' includes only comparators 34, 35 and gates 25, 26. This embodiment further differs in that the output of decision circuit 15 is connected through a T-delay element 61 to the first tap of the feedback filter 60' and to the inputs of delay elements 22, 23. The first and second taps of feedback filter 60' are separated from each other, and the output of selector circuit 70' is connected to the second tap of the filter 60'.

Since it is known that a T-delayed multipath component is the dominant component, it is sufficient to take account only of this component in a situation where it is usually likely to collide with a multipath component that propagates over a very long path. The output of delay element 61 is the decision symbol corresponding to such a T-delayed multipath component. The output of this delay element is coupled to multiplier 171 where it weighted by coefficient d_1, producing a signal for canceling the T-delayed multipath component at the output of subtractor 14. Simultaneously with the arrival of the T-delayed multipath component, a τ_1-delayed multipath component of a previous symbol is received and correlation is detected by correlator 31, resulting in the gate 25 being open to pass the τ_1-delayed decision symbol $A_{-\tau 1}$ to the second tap of feedback filter 60' where it is multiplied by coefficient d_2 in the multiplier 17_2, providing a signal for canceling the T_1-delayed multipath component at the output of subtractor 14. Multipath components arriving at successive T-intervals following the τ_1-delayed multipath component are canceled as the τ_1-delayed decision symbol is shifted along the feedback filter 60'. Similar events occur with respect to a τ_2-delayed multipath component and those following it. In this case, correlator 32 produces an output which opens the gate 26 to pass the output of delay element 23 to the second tap of filter 60'.

In this modified embodiment, the output signal Z of the feedback filter 60' is given as follows:

$$Z = -d_1 \cdot A_{-1} - \sum_{i=L}^{+\infty} d_i \cdot A_{0-i} \qquad (15)$$

where L corresponds to τ_1 or τ_2. It is seen that the first term of Equation (15) represents the output of feedback filter 60' for canceling the T-delayed multipath component associated with the transmitted symbol a_0, the second term representing the filter output when canceling those components associated with the previously transmitted symbol $a_{-\tau 1}$

or a_{-t2}.

If there is a 2T-delayed multipath component of substantial magnitude in addition to the T-delayed component, an embodiment shown in Fig. 5 is suitable. This embodiment is similar to those of the Fig. 4 embodiment with the exception that it includes delay elements 62 and 63 of 2T-delay time, a correlator 64 and a gate 66. Correlator 64 provides detection of a correlation between the symbol x_1 and the output of delay 63 and gate 66 is connected between delay 62 and the second input of feedback filter 60'. Since there is a likelihood of the 2T-delayed multipath component time-coincident with a multipath component associated with an earlier-transmitted symbol a_{-t1} or a_{-t2}, selector 70" includes a maximum detector 65 for comparing the outputs of correlators 64, 31 and 32 with each other to find which one has the highest correlation value and sūpply a gate-on pulse to one of gates 66, 25 and 26 corresponding to the correlator that produces the highest correlation value.

In this way, the multipath component of highest magnitude is selected in preference over other simultaneously arriving multipath components and the associated delayed decision symbol is selected in preference over other delayed decision symbols by selector circuit 70" and applied to the second tap of feedback filter 60', which cancels the highest magnitude multipath component at the output of subtractor 14.

Claims

1. A decision feedback equalizer comprising:

   sensor means (10_1- 10_N, 11_1-11_N) for receiving transmitted signals and recovering baseband symbols from the received signals;
   forward filter means (1) for weighting the recovered baseband symbols with first coefficients so that precursor multipath components of a transmitted symbol are canceled and combining the weighted baseband symbols to produce an output signal;
   a plurality of first delay means (27-29) for providing delays to one of said baseband symbols of the sensor means (10_1-10_N, 11_1-11_N) to produce a short-delayed baseband symbol and a long-delayed baseband symbol;
   a plurality of correlator means (30-32) for detecting correlations between said one of the baseband symbols and said short- and long-delayed baseband symbols;
   a plurality of second delay means (21-23) for providing delays to a decision symbol to produce a short-delayed decision symbol and a long-delayed decision symbol;
   selector means (33-35, 24-26) responsive to a correlation detected by one of said correlator means for selecting one of the short- and long-delayed decision symbols of the second delay means (21-23);
   feedback filter means (60) for shifting the delayed decision symbol selected by the selector means along a tapped-delay line to produce successively shifted decision symbols, weighting the successively shifted decision symbols with second coefficients and combining the weighted decision symbols to produce an output signal that cancels postcursor multipath components of said transmitted symbol;
   means (14) for combining the output signals of said forward filter means (1) and said feedback filter means (60) to produce a pre-decision symbol; and
   decision means (15) for producing a decision output from the pre-decision symbol and applying the decision output to said plurality of second delay means (21-23) as said decision symbol.

2. A decision feedback equalizer as claimed in claim 1, wherein said sensor means comprises an array of spaced sensors (10_1-10_N, 11_1-11_N), further comprising:

   decision error detector means (19, 20) connected to said decision means (15) for detecting a decision error contained in the decision symbol;
   a plurality of first update circuits (40_1-40_N) for producing a plurality of weight coefficients from the baseband symbols of said sensors (10_1-10_N, 11_1-11_N) and the decision error of said decision error detector (19, 20) and supplying said weight coefficients to said forward filter means (1) as said first coefficients; and
   a plurality of second update circuits (50_1-50_M) for producing a plurality of tap-weight coefficients from said successively shifted decision symbols of said feedback filter means (60) and the decision error of said decision error detector (19, 20) and applying the tap-weight coefficients to said multipliers (17) of the feedback filter means as said second coefficients.

3. A decision feedback equalizer comprising:

   sensor means (10_1-10_N, 11_1-11_N) for receiving transmitted signals and recovering therefrom baseband sym-

bols;
forward filter means (1) for weighting the recovered baseband symbols with first coefficients so that precursor multipath components of a transmitted symbol are canceled and combining the weighted baseband symbols to produce an output signal;
first delay means (28-29) for providing a long delay to one of said baseband symbols from the sensor means (10_1-10_N, 11_1-11_N) to produce a long-delayed baseband symbol;
first correlator means (31-32) for detecting a correlation between said one of the baseband symbols and the long-delayed baseband symbol;
second delay means (22-23) for providing a long delay to a decision symbol to produce a long-delayed decision symbol;
third delay means (61) for providing a first short delay to a decision symbol to produce a first short-delayed decision symbol;
selector means (34-35, 64, 65, 25-26, 66) responsive to the correlation detected by said first correlator means for selecting the long-delayed decision symbol of said second delay means (22-23);
feedback filter means (60) for weighting said first short-delayed decision symbol from said third delay means (61) with a second coefficient to produce a first output signal that cancels a postcursor multipath component of said transmitted symbol, and successively shifting said long-delayed decision symbol selected by the selector means along a tapped delay line to produce successively shifted decision symbols, weighting the successively shifted decision symbols with third coefficients, and combining the weighted decision symbols to produce a second output signal that cancels postcursor multipath components of a symbol transmitted earlier than said transmitted symbol;
means (14) for combining the output signals of said forward filter means (1) and said feedback filter means (60) to produce a pre-decision symbol; and
decision means (15) for producing a decision output from the pre-decision symbol and applying the decision output to said second and third delay means (22-23, 61) as said decision symbol.

4. A decision feedback equalizer as claimed in claim 3, further comprising:

fourth delay means (63) for providing a second short delay to said one of the baseband symbols to produce a second short-delayed baseband symbol;
second correlator means (64) for detecting a correlation between said one of the baseband symbols and said second short-delayed baseband symbol;
fifth delay means (62) for providing a second short delay to said decision symbol from said decision means (15) to produce a second short-delayed decision symbol;
wherein said selector means comprises:
maximum detector means (65) for comparing output signals of said first and second correlator means (31-32, 64) and producing an output signal indicating which one of the output signals has a highest magnitude; and
a plurality of gates (25-26, 66) responsive to the output signal of said maximum detector means (65) for applying one of the long-delayed decision symbol and the second short-delayed decision symbol to the second input terminal of said feedback filter means (60').

5. A decision feedback equalizer as claimed in claim 3, wherein said sensor means comprises an array of spaced sensors (10_1-10_N, 11_1-11_N), further comprising:

decision error detector means (19, 20) connected to said decision means (15) for detecting a decision error contained in the decision symbol;
a plurality of first update circuits (40_1-40_N) for producing a plurality of weight coefficients from the baseband symbols of said sensors (10_1-10_N, 11_1-11_N) and the decision error of said decision error detector (19, 20) and supplying said weight coefficients to said forward filter means (1) as said first coefficients; and
a plurality of second update circuits (50_1-50_M) for producing a plurality of tap-weight coefficients from said successively shifted decision symbols of said feedback filter means (60) and the decision error of said decision error detector (19, 20) and applying the tap-weight coefficients to said multipliers (17) of the feedback filter means as said second and third coefficients.

6. A method for canceling multipath components of a transmitted symbol, comprising the steps of:

a) receiving transmitted signals and recovering baseband symbols from the received signals;
b) weighting said recovered baseband symbols by coefficients so that precursor multipath components of a

transmitted symbol are canceled and combining the weighted baseband symbols to produce a first pre-decision symbol;

c) providing delays to one of said baseband symbols to produce a short-delayed baseband symbol and a long-delayed baseband symbol and providing delays to a decision symbol to produce a short-delayed decision symbol and a long-delayed decision symbol;

d) determining whether a correlation exists between said one of the baseband symbols and said short- and long-delayed baseband symbols and selecting one of the short- and long-delayed decision symbols depending on which one of said short- and long-delayed baseband symbols said correlation is detected;

e) successively shifting the decision symbol selected by step (d) along a tapped-delay line to produce successively shifted decision symbols, weighting the successively shifted decision symbols with coefficients, and combining the weighted decision symbols to produce a canceling signal which cancels postcursor multipath components of said transmitted symbol;

f) combining the canceling signal with said first pre-decision symbol of step (b) and producing a second pre-decision symbol; and

g) making a decision on said second pre-decision symbol and producing a decision output and repeating step (c) by using the decision output as said decision symbol.

7. A method for canceling multipath components of a transmitted symbol, comprising the steps of:

a) receiving transmitted signals and recovering baseband symbols from the received signals;

b) weighting said recovered baseband symbols with coefficients so that precursor multipath components of a transmitted symbol are canceled and combining the weighted baseband symbols to produce a first pre-decision symbol;

c) providing a delay to one of said baseband symbols to produce a long-delayed baseband symbol and providing delays to a decision symbol to produce a short-delayed decision symbol and a long-delayed decision symbol;

d) weighting the short-delayed decision symbol of step (c) with a coefficient to produce a first canceling signal that cancels a short-delayed postcursor multipath component of said transmitted symbol;

e) determining whether a correlation exists between said one of the baseband symbols and said long-delayed baseband symbol and selecting the long-delayed decision symbol if said correlation is detected;

f) successively shifting the long-delayed decision symbol selected by step (e) along a tapped-delay line to produce successively shifted decision symbols, weighting the successively shifted decision symbols with coefficients, and combining the weighted decision symbols to produce a second canceling signal that cancels long-delayed postcursor multipath components of a symbol transmitted earlier than said transmitted symbol;

g) combining each of the first and second canceling signals with said first pre-decision symbol of step (b) and producing a second pre-decision symbol; and

h) making a decision on said second pre-decision symbol and producing a decision output and repeating step (c) by using the decision output as said decision symbol.

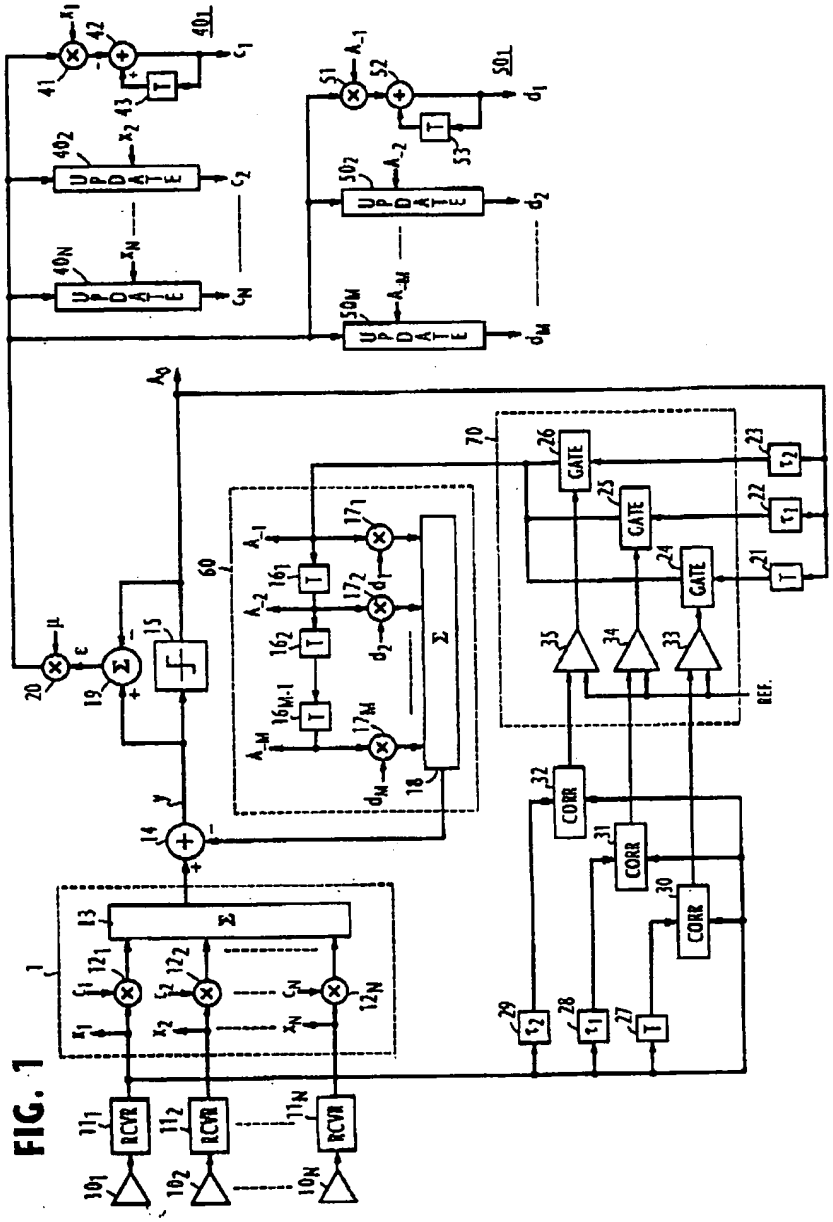


FIG. 1

FIG. 2

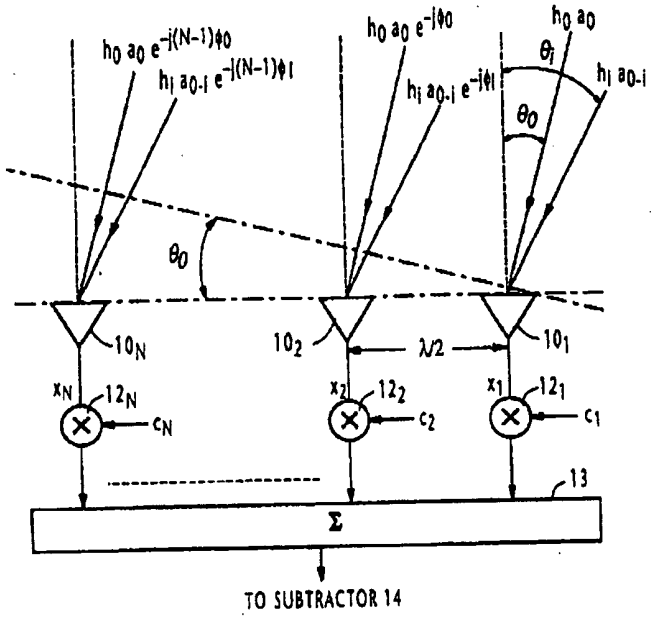


FIG. 3A

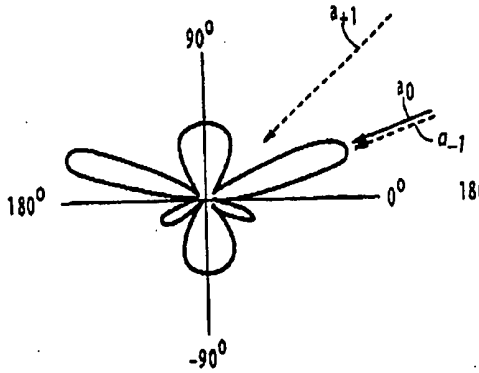


FIG. 3B

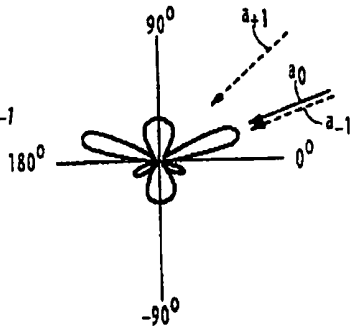
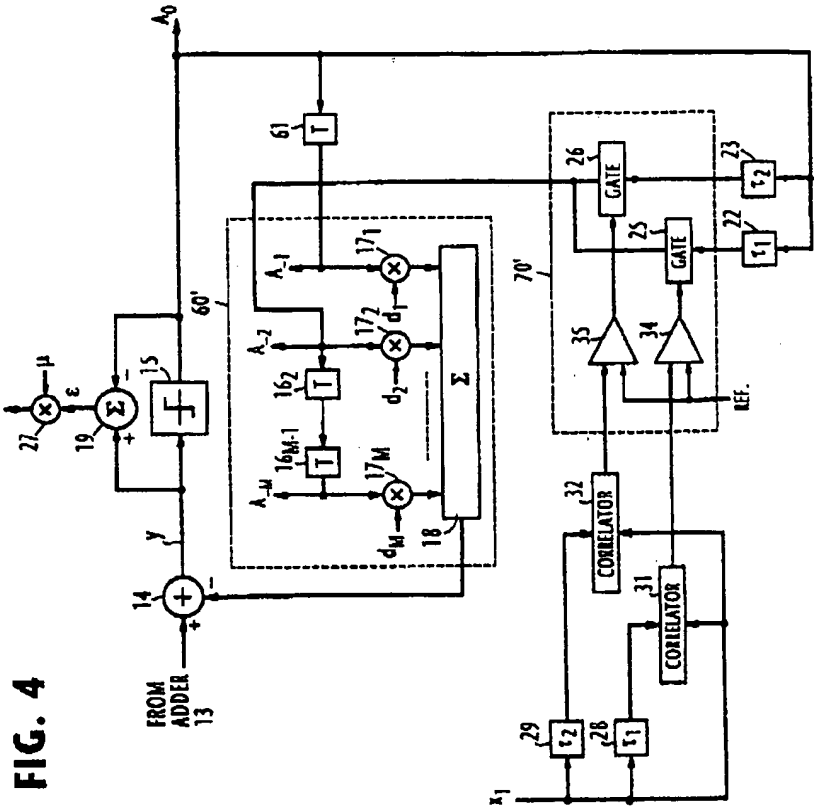


FIG. 4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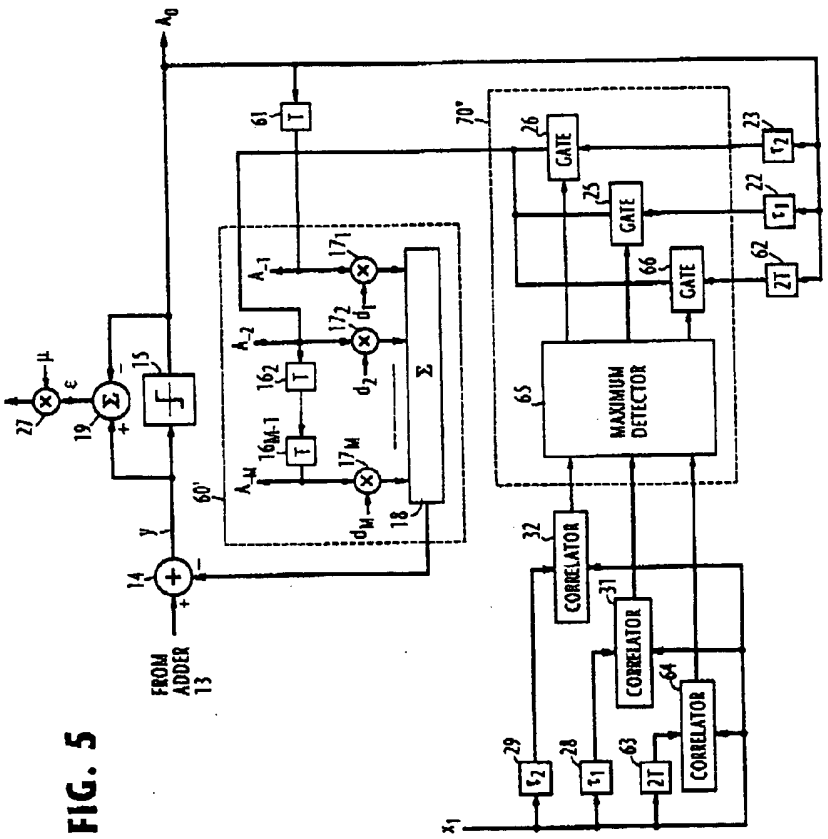

FIG. 5

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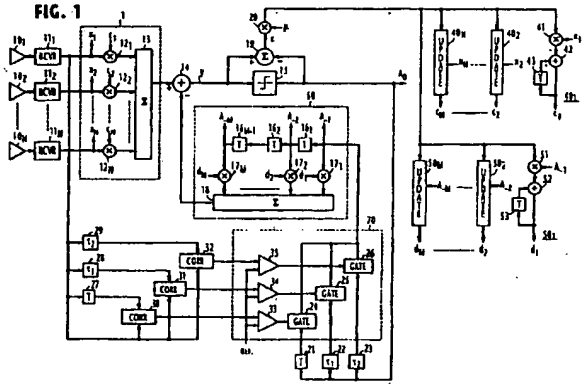
(54) Decision feedback equalizer for cancelling short- and long-multipath components using correspondingly delayed decision symbols

(57) In a decision feedback equalizer, transmitted signals are received by an array of antennas and baseband symbols are recovered. A forward filter provides weighting of the recovered baseband symbols with first coefficients so that precursor multipath components of a transmitted symbol are canceled and combines the weighted symbols. A set of first delay elements provide respective delays to one of the baseband symbols to produce a short- and a long-delayed baseband symbol. A set of correlators is provided for detecting correlations between the baseband symbol and the short- and long-delayed baseband symbols. A set of second delay elements provide respective delays to a decision symbol to produce a short- and a long-delayed decision symbol. A selector is responsive to a correlation detected by one of the correlators for selecting one of the short- and long-delayed decision symbols. A feedback filter shifts the selected decision symbol along a tapped-delay line to produce successively shifted decision symbols, multiplies them with second coefficients and combines the multiplied decision symbols to produce an output signal that cancels postcursor multipath components of the transmitted symbol. The output signals of the forward and feedback filters are combined to produce a pre-decision symbol which is used by a decision circuit to produce a decision output for coupling to the second delay elements as the aforesaid decision symbol.

FIG. 1



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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.6)
A	GB 2 238 932 A (NIPPON ELECTRIC CO) 12 June 1991 * figures 5,6 *	1,3,6,7	H04L25/03
A	US 4 912 557 A (FAROUDJA YVES C) 27 March 1990 * column 2, line 42 - column 3, line 35 *	1,3,6,7	
A	EP 0 387 498 A (KOMMUNIKATIONS ELEKTRONIK) 19 September 1990 * figure 1 *	1,3,6,7	
D,A	EP 0 604 956 A (NIPPON ELECTRIC CO) 6 July 1994 * figure 1 *	1,3,6,7	
A	EP 0 565 104 A (NIPPON ELECTRIC CO) 13 October 1993 * figures 2,3 *	1,3,6,7	

TECHNICAL FIELDS SEARCHED (Int.Cl.6)

H04L
H04B
H04N

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	18 June 1998	Goulding, C

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